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(54) **OMNI-DIRECTIONAL RADIATOR FOR MULTI-TRANSDUCER ARRAY**

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*H04R 25/00* (2006.01)

(52) **U.S. Cl.** ..... **367/133; 367/131; 367/153; 381/182**

(58) **Field of Classification Search** ..... 367/133, 367/153; 381/182

See application file for complete search history.

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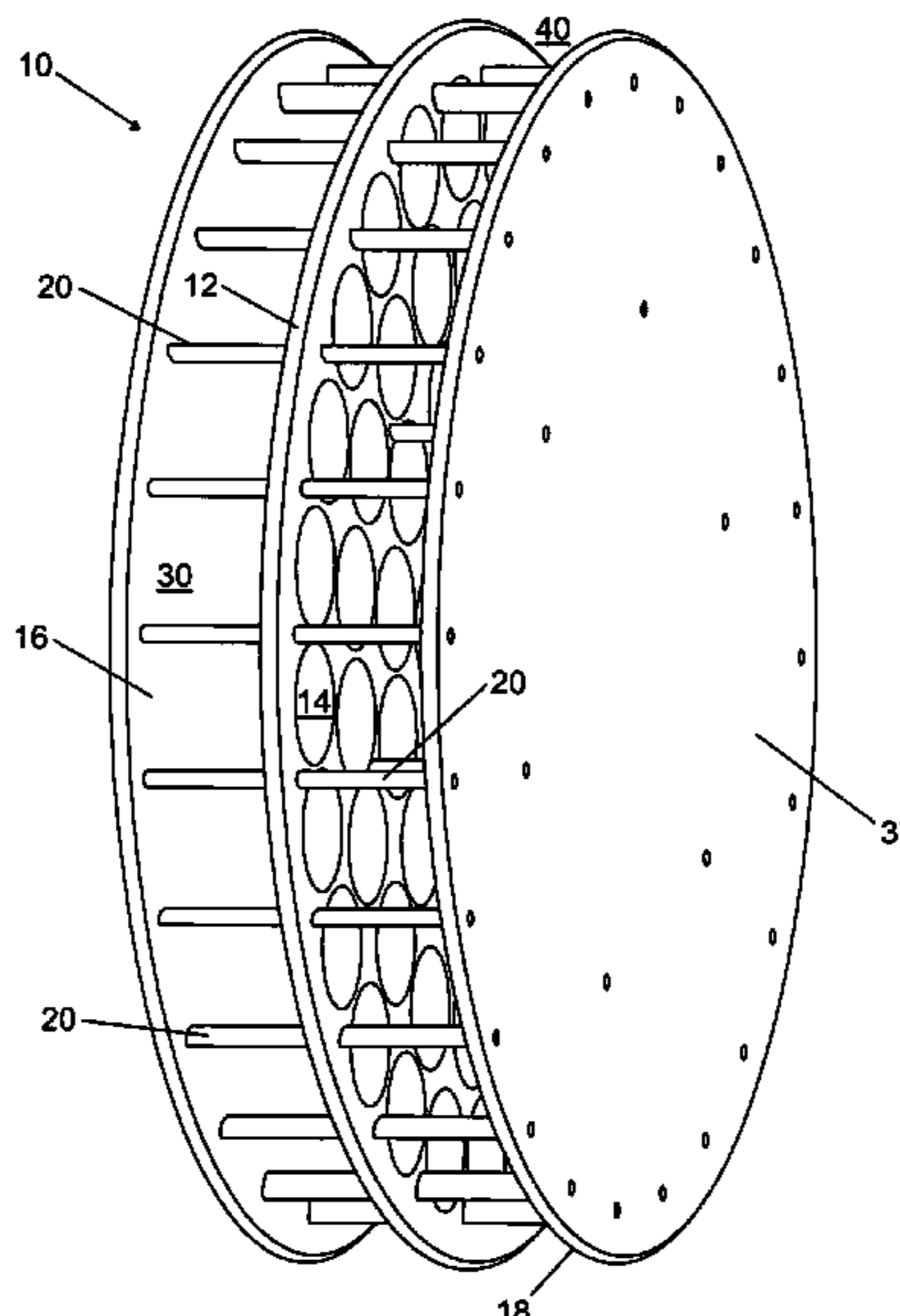
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(57) **ABSTRACT**

An omni-directional acoustic horn for applications in a liquid transmission medium deploys a plurality of transducers distributed along an interior face of the horn to radiate against an opposed surface. The arrangement mimics operation at a greater depth of submergence to depress development of acoustic cavitation bubbles.

**16 Claims, 11 Drawing Sheets**



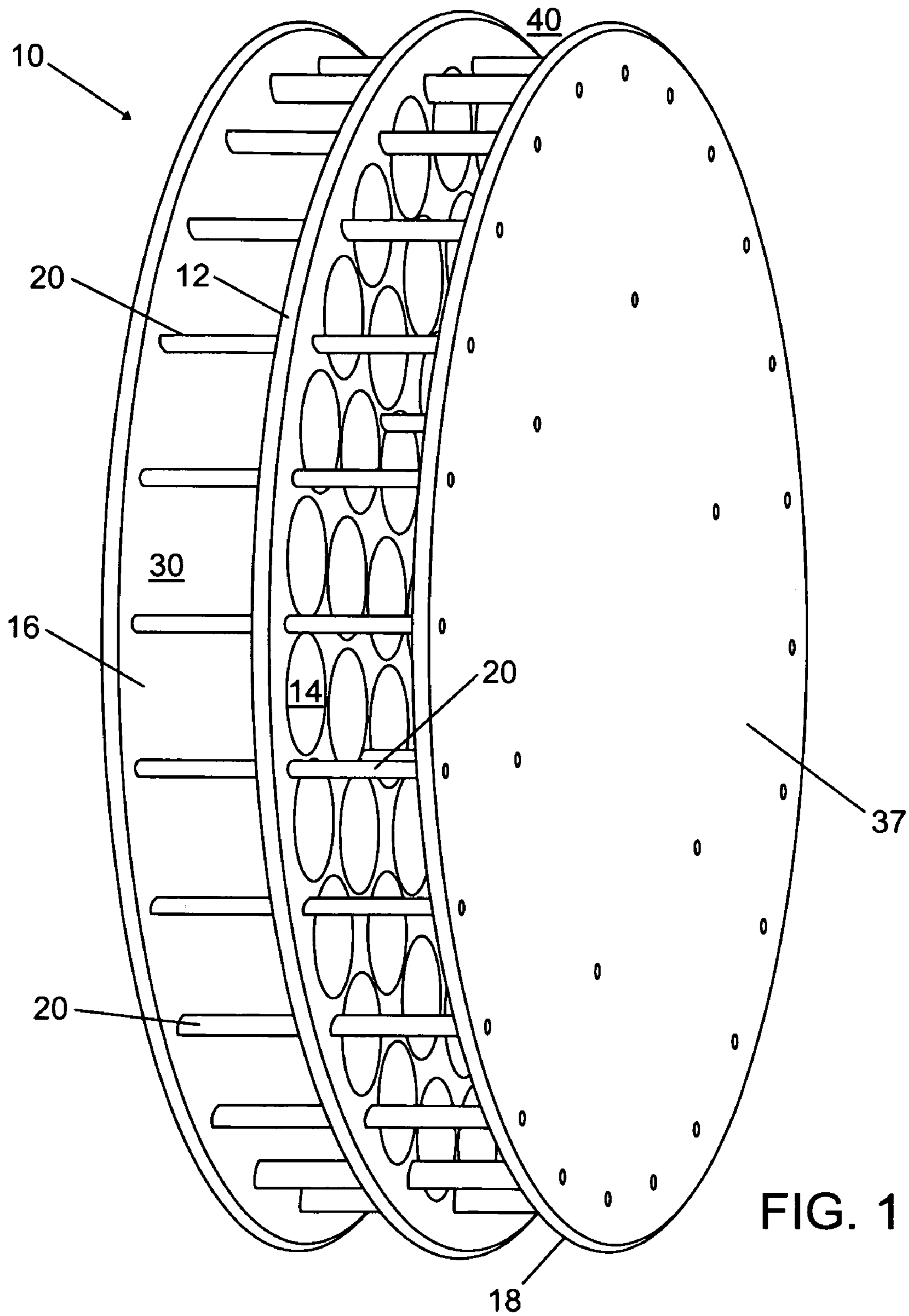
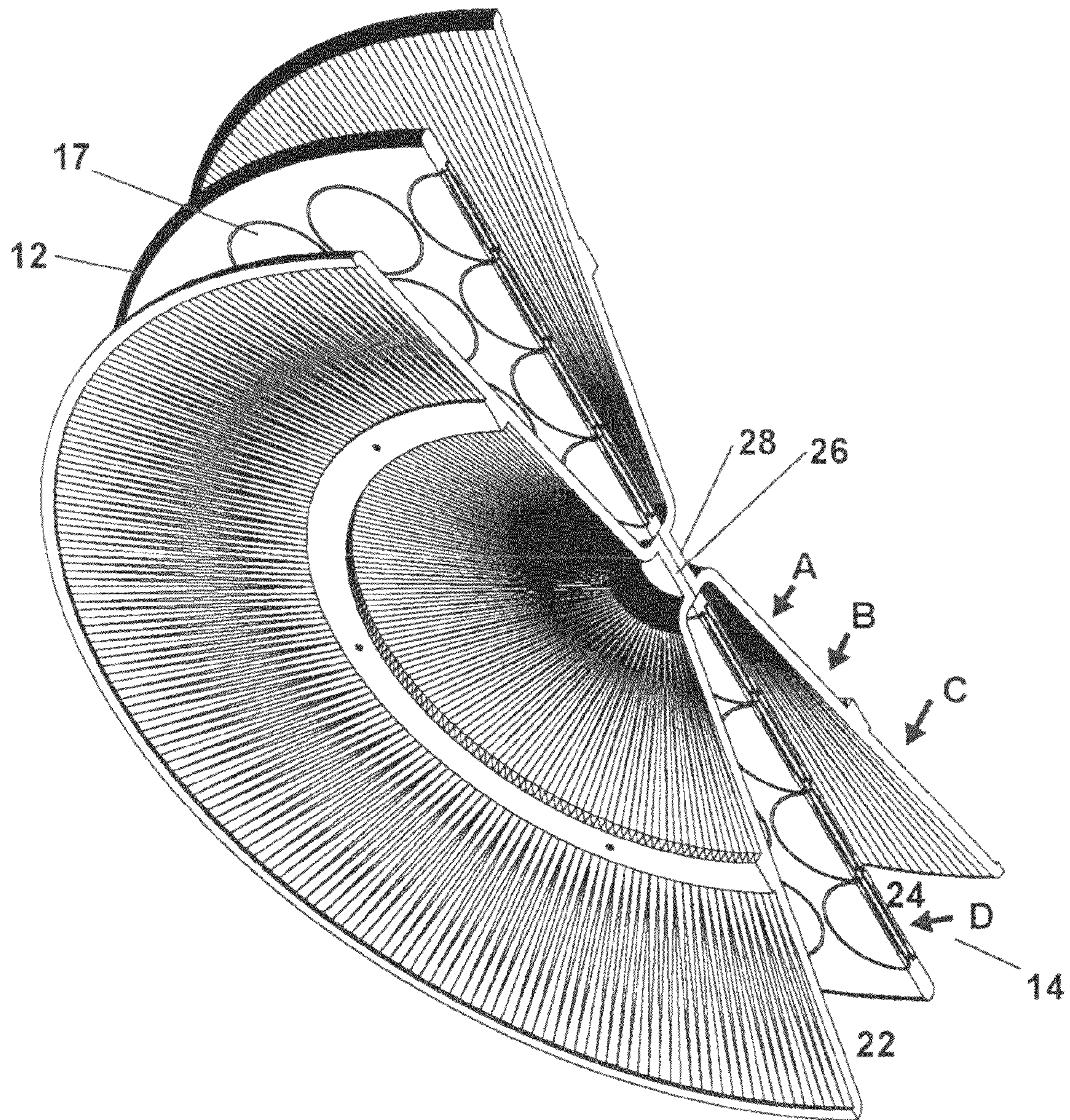


FIG. 1



FIG. 2





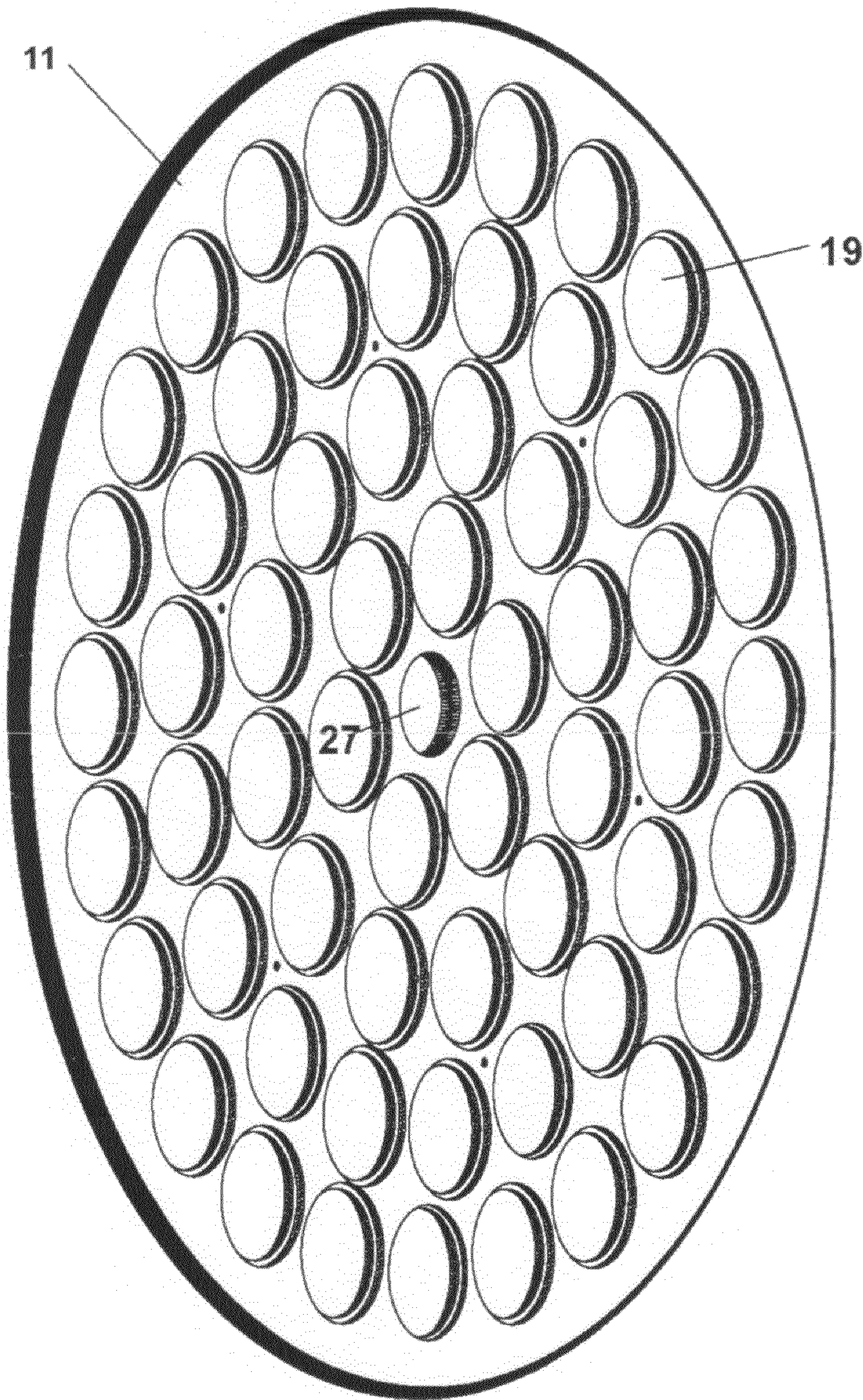
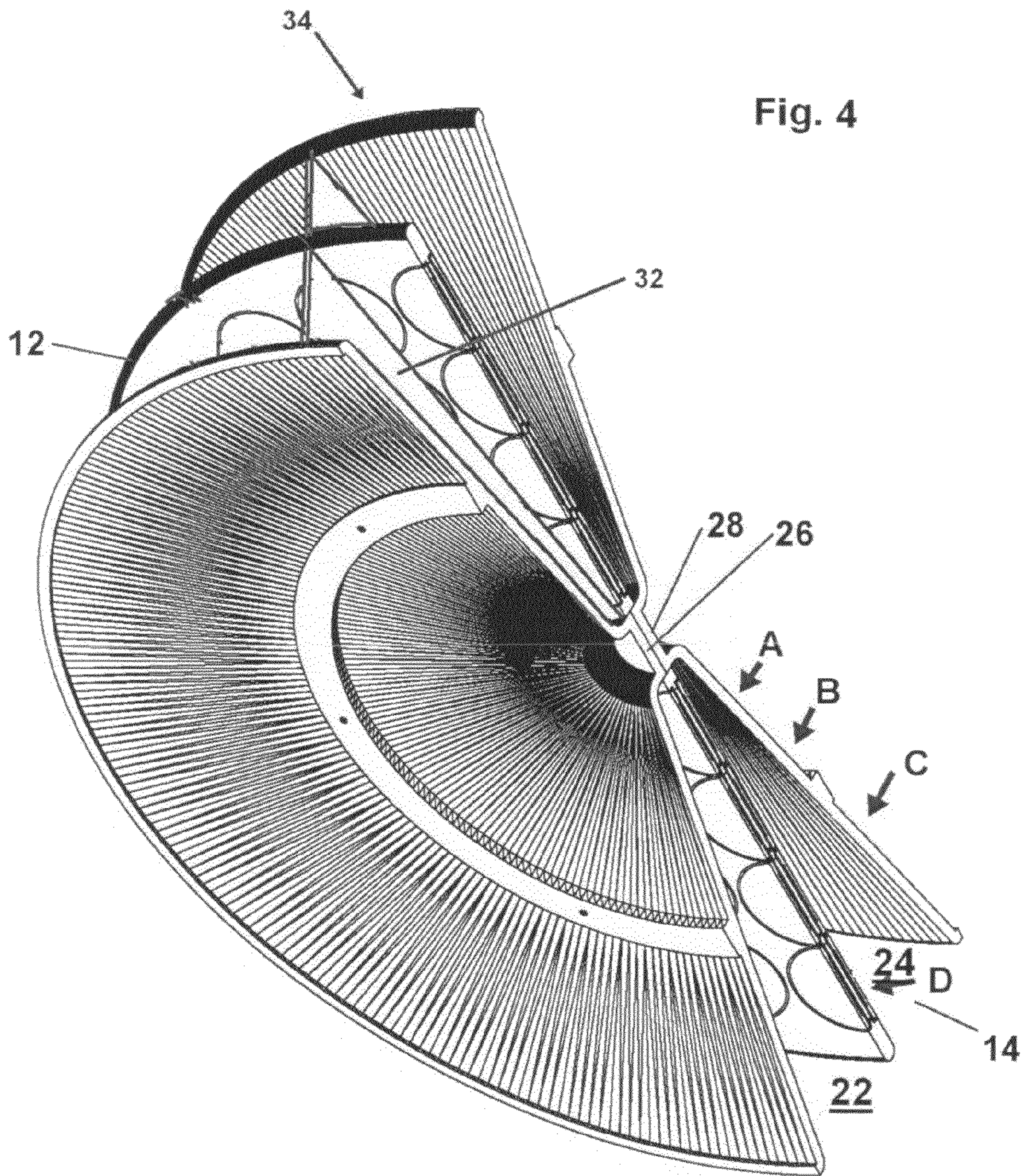
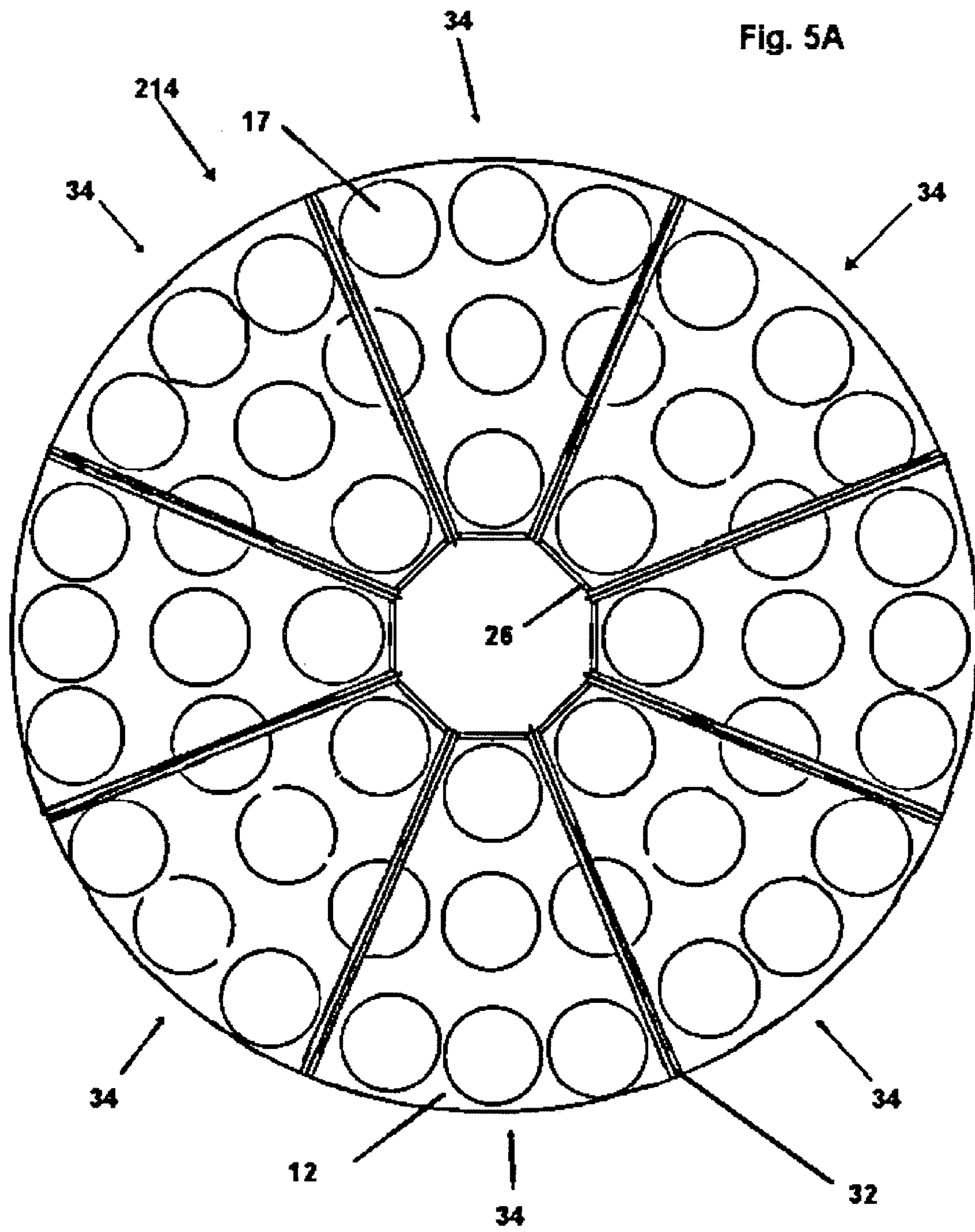


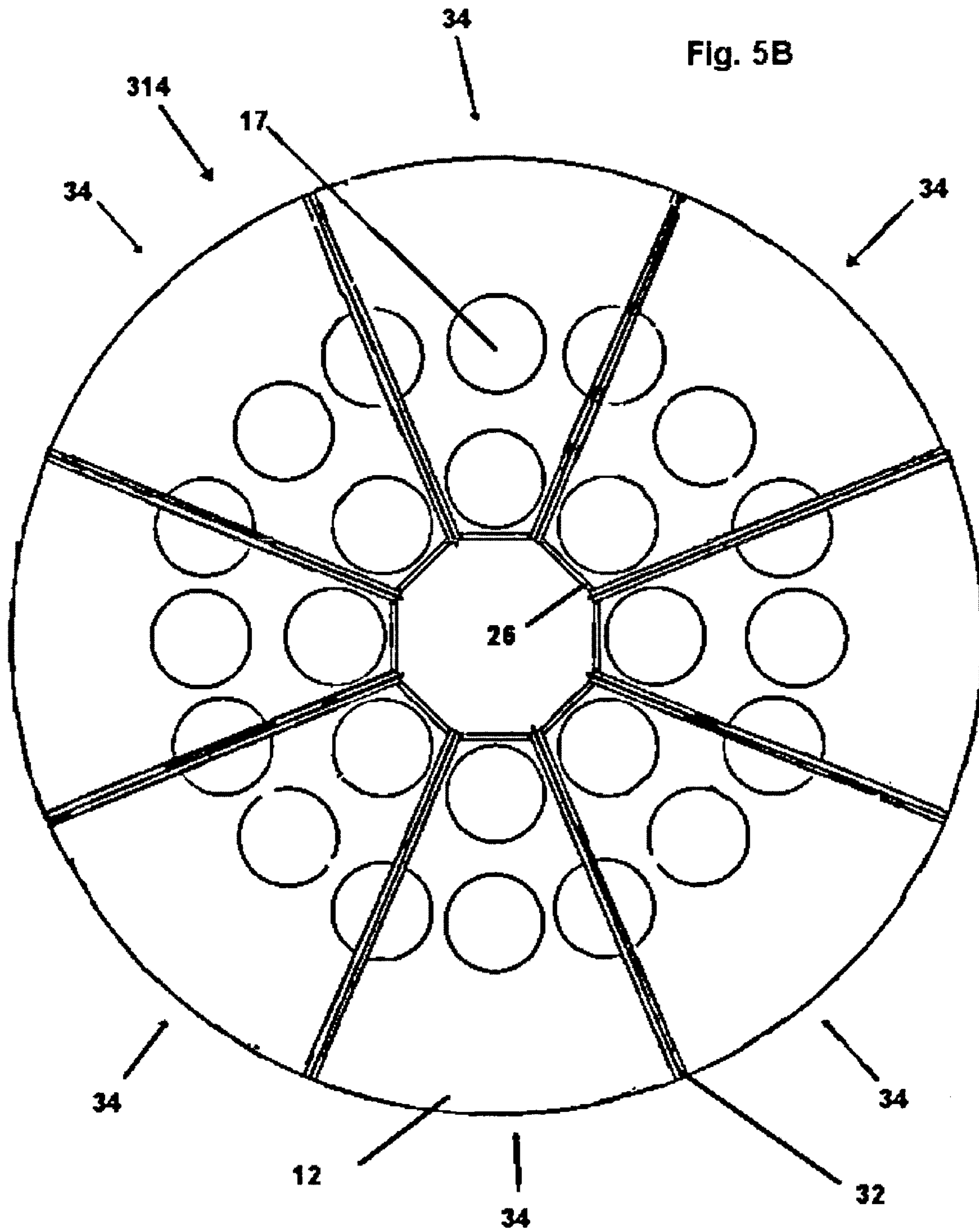
FIG. 3

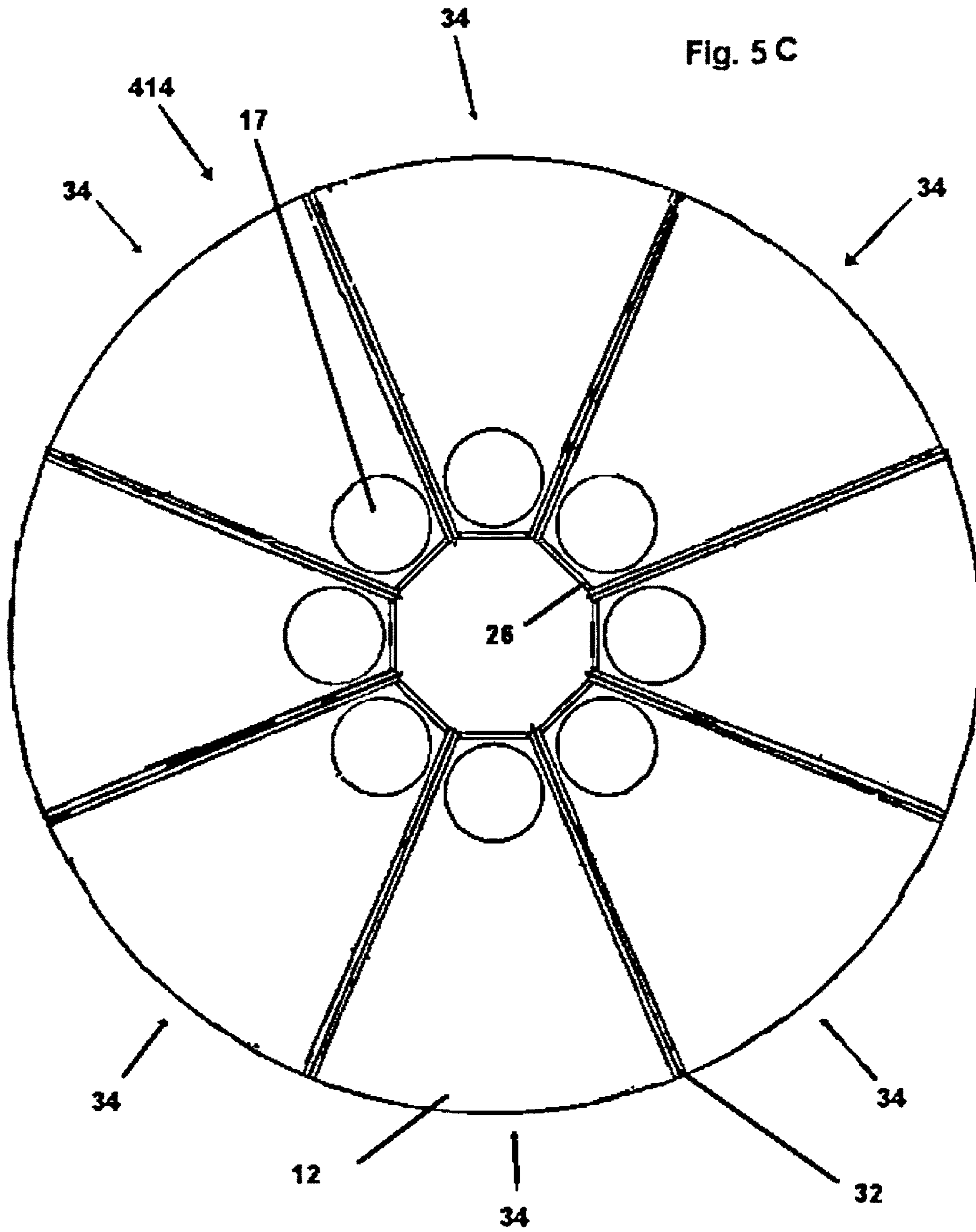














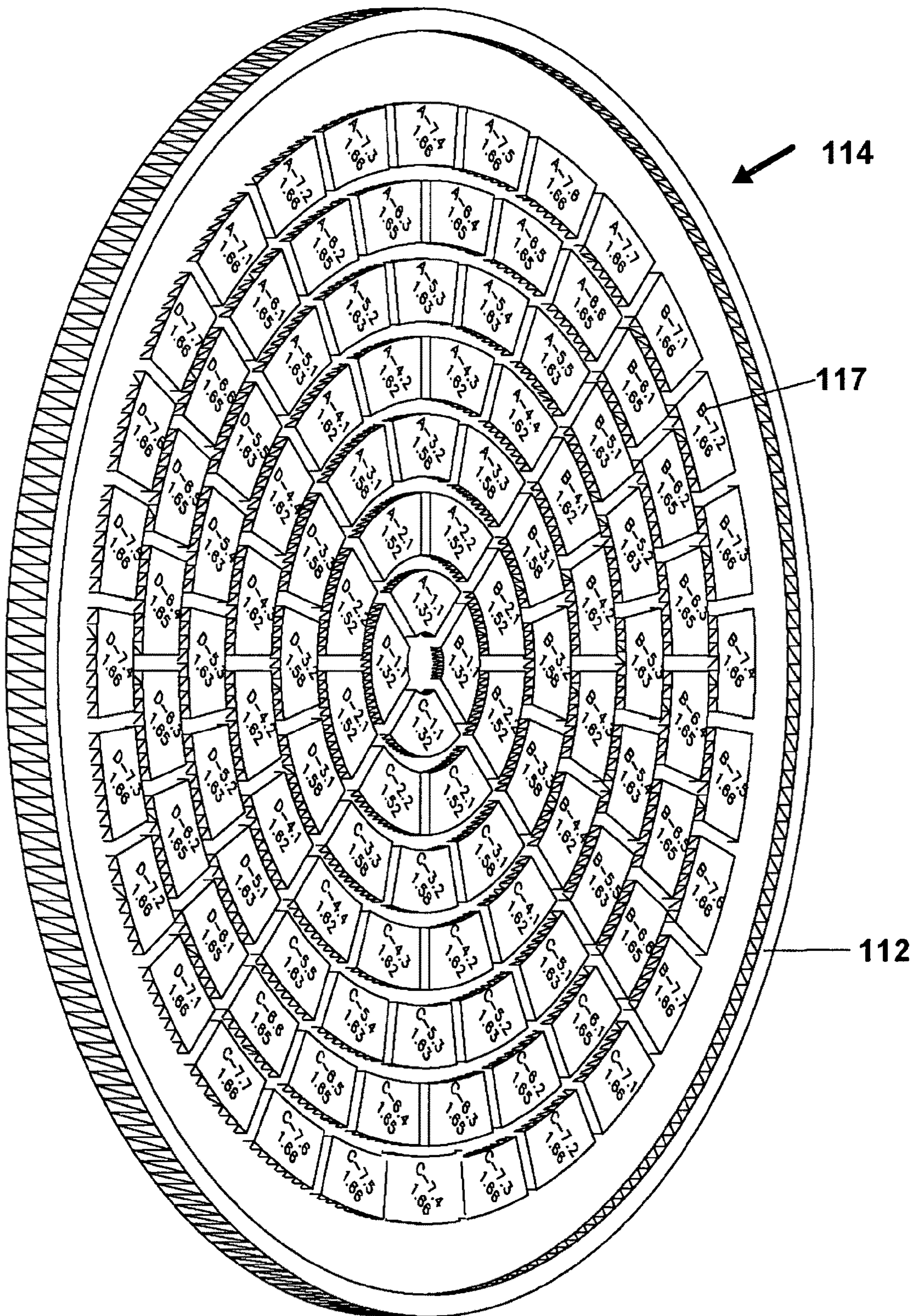


Fig. 6



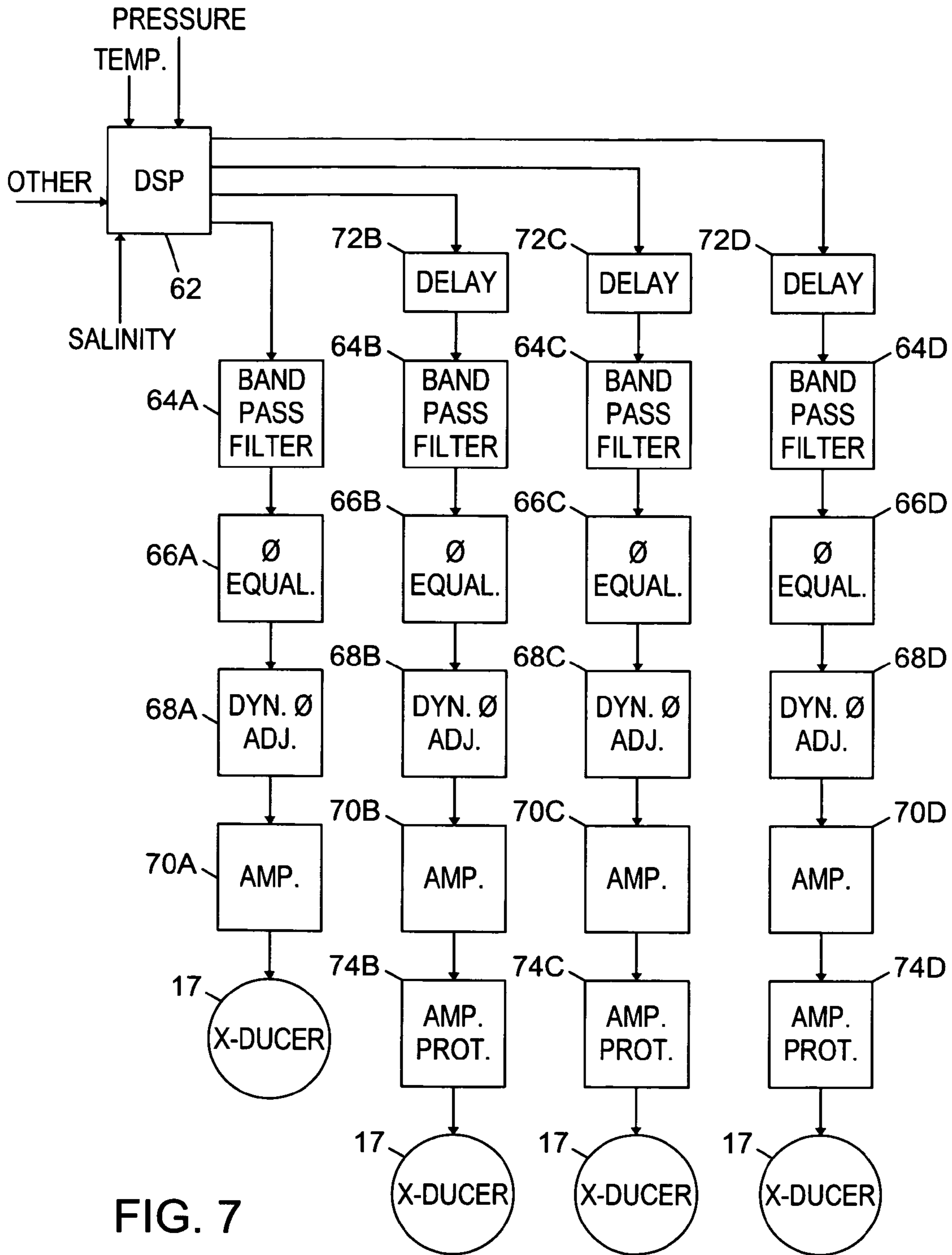


FIG. 7



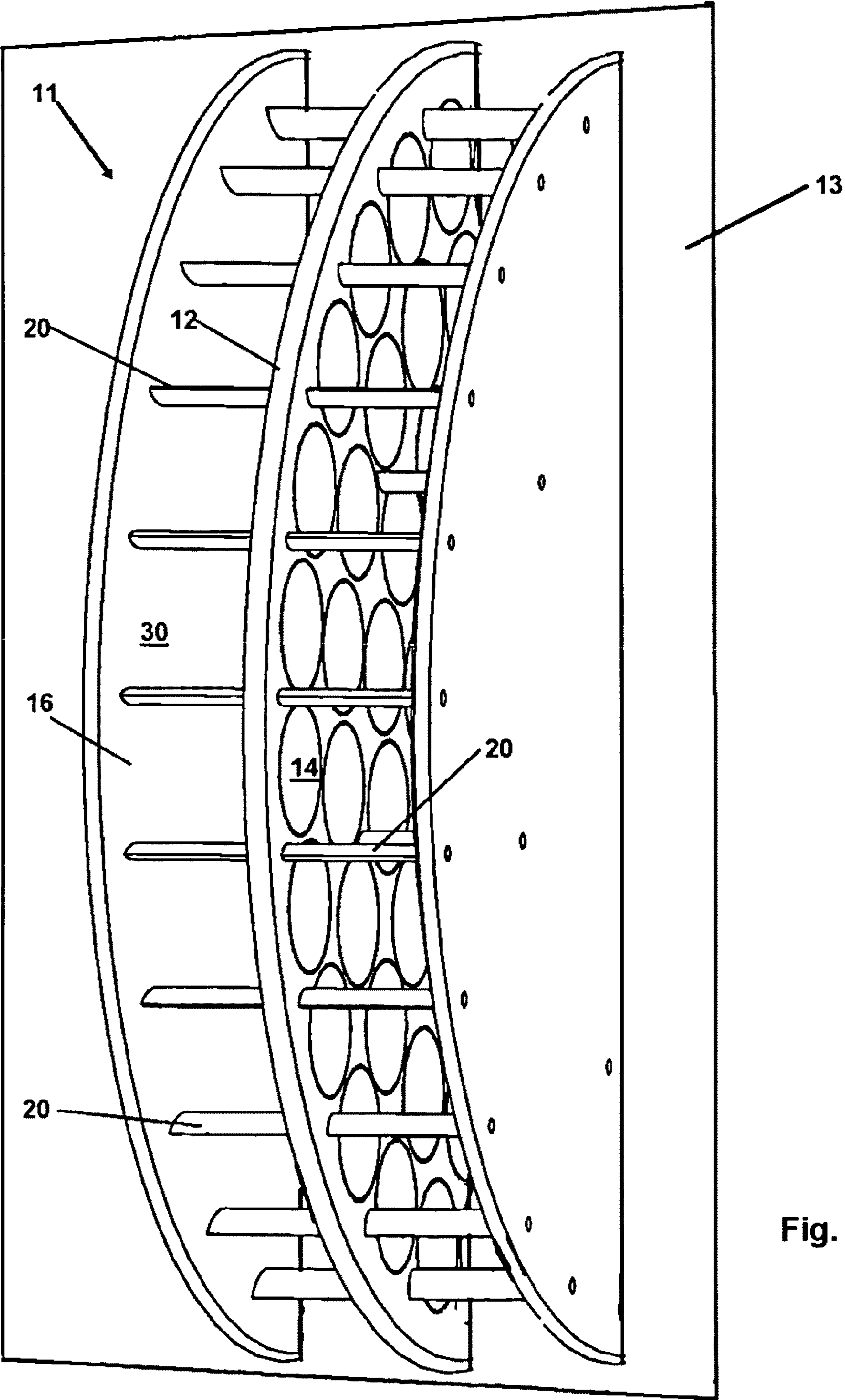


Fig. 8



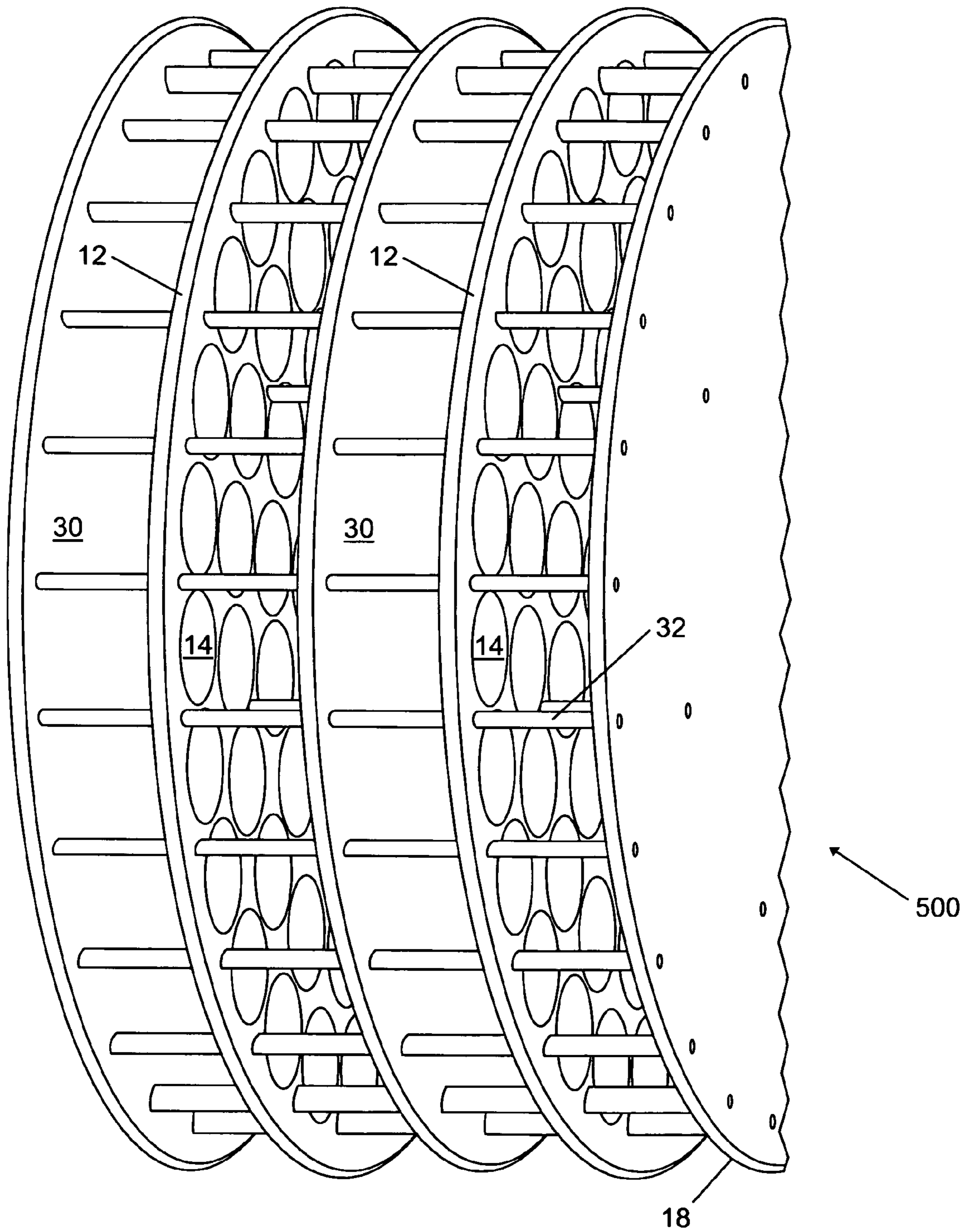


FIG. 9



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## OMNI-DIRECTIONAL RADIATOR FOR MULTI-TRANSDUCER ARRAY

### PRIORITY CLAIM

This application claims priority based on U.S. Provisional Patent Application No. 61/199,030 filed Nov. 12, 2008.

### BACKGROUND

#### 1. Technical Field

The disclosure relates to transducer arrays for producing sound, and more particularly to a high power sound source for use in liquids.

#### 2. Description of the Problem

Sound is a disturbance in the physical properties of an elastic material/medium that propagates through the material. The disturbed physical properties can be the alternation in pressure, the displacement of particles or a change in the density of the elastic material/medium. An acoustic pressure wave will have alternating zones of high and low pressure, which can be referred to as the compression and rarefaction waves. An acoustic pressure wave propagating through a liquid (and possibly through a solid) medium can produce phase changes and otherwise affect physical properties of the liquid medium due to changing pressure. Pressure drops in a liquid medium can result in the liquid medium itself turning to vapor, gasses dissolved in the liquid leaving solution, or both. In other words, bubbles can be produced. These bubbles are termed acoustic cavitation bubbles. Usually acoustic cavitation bubbles rapidly collapse, which in turn can produce intense shock waves.

Whether acoustic cavitation bubbles are a problem in a given situation depends upon the system. For example, in systems where the pressure variation is highest at the surfaces of the transducers acoustic cavitation bubbles occur along these surfaces and their occurrence decreases rapidly with increasing distance from the surface of the transducer. In such systems the transducer surfaces are vulnerable to damage from acoustic cavitation.

The acoustic cavitation phenomenon can also limit the amount of power that can be transferred from the transducer element(s) to the propagating medium and distort the resulting signal. A cavitation resistant array was proposed in U.S. Pat. No. 6,050,361 in which interstices of the sonar array between transducers was designed to match the specific acoustic impedance of water.

### SUMMARY

An omni-directional acoustic radiator provides are arcuate waveguide, which may be extended through a full circle to form a toroidal waveguide. A full toroidal waveguide includes two facing interior surfaces forming boundaries. Acoustic transducers are arranged in a constellation along one of the interior surfaces of a waveguide and face the opposed surface. The transducers are oriented to direct sound into a substantially opposed surface or boundary. The interior surface and the boundary extend outwardly from a central base or core of the waveguide and terminate at a mouth. Pressure waves propagating outwardly in the waveguide may be reinforced along a portion or substantially the full depth waveguide, including being summed in a cumulative or cascade manner, with operation of outer transducers (that is transducers closer to the mouth) being delayed and phase compensated to achieve coherent reinforcement of the pressure wave as it propagates outwardly from the core or central base. An arcu-

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ate or toroidal waveguide may be divided into channels by the use of interior radial baffles to increase output amplitude.

Additional effects, features and advantages will be apparent in the written description that follows.

### BRIEF DESCRIPTION OF THE DRAWINGS

The contribution to the art believed novel is set forth in the appended claims. The preferred mode of use will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

FIG. 1 is a perspective view of an omni-directional acoustic radiator in accord with one embodiment of the invention.

FIG. 2 is an isometric view of a sectioned omni-directional acoustic radiator.

FIG. 3 is a perspective view of an disk baffle for the omni-directional acoustic radiator of FIG. 1.

FIG. 4 is an isometric view of a sectioned omni-directional acoustic radiator with a radial baffle.

FIGS. 5A-C are top plan views of disk baffles having carrying different possible multi-transducer arrays.

FIG. 6 is a perspective view of an alternative disk baffle.

FIG. 7 is a block schematic of drive circuitry for the radiator.

FIG. 8 is a perspective view of a section of a directional acoustic radiator with a back boundary.

FIG. 9 is a perspective view of a section of acoustic radiators stacked in a linear array.

### DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Referring now to the drawings and more particularly to FIGS. 1-2, an acoustic radiator 10 is shown. Acoustic radiator 10 may be employed to radiate sound in a liquid medium, typically fresh or sea water and can operate through a full 360-degree arc in a plane and while exhibiting minimal vertical spread over a wide operational spectrum. In an omni-directional embodiment the acoustic radiator 10 comprises a pair of toroidal waveguides 22, 24. Toroidal waveguides 22, 24 are disposed back to back and radiate in parallel. Toroidal waveguide 22 is formed between disk baffle 12 and half shell 16. Toroidal waveguide 24 is formed between disk baffle 12 and half shell 18. Toroidal waveguides 22, 24 have a disk baffle 12 in common. Toroidal waveguides 22, 24 have circular, full circumference mouths 30, 40. A face plate 37 is shown in FIG. 1 and covers a depression in the relative exterior surface of shell 18.

Toroidal waveguides 22, 24 resemble horns in some functions. Horns are conventionally employed as acoustic transformers in low impedance transmission mediums, such as air. In air a horn increases the efficiency of coupling energy from a transducer/driver to the air by constraining expansion of the air in response to transducer movement in the vicinity of the transducer. The containment functionality they provide has some application in a liquid transmission medium. Efficiency in coupling energy from a solid transducer to most liquids is much higher than it is for a gas hence the transformer function of the horn is of little consequence in a liquid medium. However, by constraining displacement of liquid medium the phenomenon of the sound wave producing a change in phase of the medium is depressed by mimicking operation of the device at a greater depth of submergence. Toroidal waveguides 22 and 24 provide a step up in pressure allowing for the cascade reinforcement of a sound wave as it propagates from the respective central bases 26, 28 of the toroidal



waveguides toward emission from mouths **30, 40** while suppressing the generation of acoustic cavitation bubbles during propagation and reinforcement of the rarefaction wave. The distance from the central bases **26, 28** to the mouths **30, 40** may be referred to as the radius or depth of the toroidal waveguides **22, 24**. In essence, it appears the device is operating at a simulated greater submergence in the liquid medium. Toroidal waveguides **22, 24** also enhance the low frequency range of the omni-directional acoustic radiator **10**.

Disk baffle **12** is based on a disk template **11**. The disk template is perforated in a number of locations **19** for the inclusion of disk shaped piezoelectric transducers **17** and exhibiting a central aperture **27** through which central bases **26, 28** of the half shells **16, 18** can be joined to form a central core. Half shells **16** and **18** are generally round, but form sloped, shallow, bowl like structures on the major surface of the half shells remote to the disk baffle **12**. The opposite major surfaces of the half shells **16** and **18**, that is, the interior surfaces facing the major surfaces of disk baffle **12**, form acoustic boundaries and cooperate with the disk baffle **12** to direct sound outwardly from the central bases **26, 28**. The interior surfaces of half shells **16** and **18** exhibit an increasing gap from the disk baffle **12** with increasing distance from the central core formed by central bases **26, 28**. When assembled an omni-directional horn-like structure is provided between one of the major faces of disk baffle **12** and a facing surface of one of half shells **16** or **18** to form one of two parallel 360° mouths **30, 40**. The arcuate mouths **30, 40** radiate sound propagated from arcuate waveguides formed between the facing surfaces.

Disk baffle **12** and half shells **16** and **18** may be fabricated in cast in aluminum alloy and polished. However, such an aluminum structure may ring when used. In order to dampen ringing, dampening elements **20** may be lodged between disk baffle **12** and the respective half shells **16, 18**.

Omni-directional radiator **10** incorporates a pair of multi-transducer arrays **14**, which in one embodiment is formed from a constellation of four concentric circular sub-arrays (A, B, C and D) of piezoelectric acoustic transducers **17** mounted through baffle **12** at locations **19**. Piezoelectric acoustic transducers **17** have opposed faces which operate in phase with one another. Baffle **12** provides one of the two surfaces for each of toroidal waveguides **22, 24**, and the transducers are to be mounted so that each of their two active faces is flush with one of the major surfaces of the baffle **12**. FIG. **2** depicts one possible interior arrangement for the transducers. However, actual devices could be cut in a similar manner to be fitted against the side of a ship or other underwater structure. In other words, the double disk arrangement could be cut in half, or quartered, etc., and a boundary disposed along the exposed interior portion to produce a sound projecting apparatus for a confined angle in a plane as illustrated in FIG. **6** where a "directional" radiator **11** includes a backing **13** which confines the radial extent of the device to half a circle.

Piezoelectric acoustic transducers **17** are conventionally provided as circular disks, though such a shape is not necessarily the best one. Toroidal waveguides propagate sound waves initiated near the central cores **26, 28** outwardly to mouths **30** and **40** while at least maintaining the amplitude of the wave as it expands circumferentially within the radiators. To obtain that result it is intended that an acoustic wave propagating outwardly in the toroidal waveguides **22, 24** be maintained at a constant or increasing pressure notwithstanding the increasing area of the wave front as it moves from the central cores to the mouths **30, 40**.

Each successive sub-array (B, C, D) of transducers **17** after the first sub-array A should add enough energy, synchronized

with the wave, to at least maintain the acoustic wave's amplitude notwithstanding the expanding circumference of the wave front. Greater efficiency is obtained if energy is added continuously as the wave propagated outwardly. This objective would be best served by making the transducers as small as possible, at least in the directions moving radially outwardly from the central cores **26, 28**. Ideal transducers would be circular ribbons of minimal width and successively greater diameters, centered on the central cores **26, 28** and essentially blanketing the available surface of the baffle **12**. The brake shoe shaped transducers of FIG. **6** mimic this arrangement.

Prototype embodiments of an omni-directional acoustic radiator **10** employing four rings A-D in the multi-transducer array **14** of transducers **17** indicated that the transducers **17** in the inner rings A and B contributed almost all of the gain in amplitude of the wave front while ring C contributed a much smaller amount of additional amplitude and ring D contributed virtually none. However, operation of the outer rings C and D did expand the band width of the omni-directional acoustic radiator **10** in the low frequency range. FIGS. **5A-C** illustrate alternative constellations of multi-transducer arrays **214, 314, 414** providing three rings, two rings and one ring of transducers **17**, respectively.

FIG. **4** illustrates the use of a radial baffle **32** to improve output gain of omni-directional acoustic radiators **10**. Radial baffles **32** divide the toroidal waveguides **22, 24** into a plurality of radial channels **34**. Greater amplitude gain is obtained if the toroidal waveguides **22, 24** are sectioned into a plurality of radial channels **34** using radial baffles **32**. In FIG. **4** radial baffle **32** is shown extending from disk baffle **12** to the interior surfaces of the half shells **22, 24**. FIGS. **5A-C** show eight (optional) radial baffles **32** extending from a central core (here central core **26**) to the outer edge perimeter of the disk baffle **12**. The eight radial baffles **34** divide a toroidal waveguide into eight radial channels **34** resulting in improved amplitude output from the device, particularly for radial waveguides incorporating multi-transducer arrays with where transducers **17** are located in greater proximity to the outer edge of disk baffle **12**.

FIG. **6** illustrates a possible alternative arrangement of arcuate transducers **117** mounted on a baffle **112**. Here there are seven rings or circular arrays of transducers **117**, with the transducers being closely tiled on the illustrated surface of the baffle **112** to effectively cover more of the surface of the baffle. It is expected that there will be an increasing number of transducers in each successive ring of transducers moving outwardly along the radiator. This assumes that the transducers used in the sub-arrays are identical, and in order to increase the active area of the transducers in step with the increasing area of the wave front it will be necessary to increase their number. However, it is more properly thought of as increasing the surface area of the transducers with each outward move along the radiator, not the number of transducers and to keep the proportional area of the circle along which energy is injected constant.

It is believed to be possible to insert more energy into the propagating sound wave, using the sub-array arrangement of transducers **17** and radiators **22** and **24**, than could ever be achieved using a single transducer without incurring acoustic cavitation. It may be possible to support a cascade buildup of the acoustic wave, and maintain control over its spectrum, without incurring the sound pollution resulting from acoustic cavitation. To achieve this the innermost sub-array A is operated at relatively low level, with each successive sub-array B, C and D operating at higher energy input levels, but not at levels resulting in cavitation along their respective active surfaces. The continuous insertion of energy to maintain a



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constant or increasing signal amplitude, while it has particular advantages to the underwater application of the preferred embodiment, has application to radiator systems used in atmospheric applications. The increasing pressure of the sound wave itself may assist in the suppression of acoustic cavitation. The number of sub-arrays active (or present) can vary from one upward.

Piezoelectric devices have been commonly employed to construct acoustic transducers for use in sonar systems, particularly sonar system for use underwater. These devices develop electrical potential under changes in pressure which requires that the final stage amplifiers for the transducers be protected against feedback electrical power from an acoustic wave passing over a transducer.

Referring to FIG. 7, a block diagram circuit 60 illustrates a mechanism for control over a transducer array constructed from circular transducers 17. Block diagram circuit 60 is adapted for use of the system in a water environment, though its use in other liquid environments should not be discounted. A variety of factors must be taken into account in generating a high intensity underwater sound pulse, such as water depth (represented by pressure), salinity of the water and temperature of the water. All of these factors affect water density and the speed of sound in water. In addition, other factors may be relevant to consideration of the possible onset of acoustic cavitation, such as the concentration of dissolved gasses, such as oxygen and nitrogen, in the water. Such measurements as are available (typically pressure, temperature and salinity) are provided a digital signal processor 62 which adjusts the base wave form for the four channels (A, B, C, D) and generates a delay factor for transmission to the three relatively outboard channels (B, C, D). The circuit channels correspond to the four sub-arrays A, B, C, D of transducers provided in the preferred embodiment. Final amplifier stages 70A-D provide differential levels of amplification depending upon the number of transducers in the sub-array (A-D). The omni-directional radiator 10 may also be operated as a highly directional receiver.

Channels A, B, C and D are schematically substantially identical save that channel A does not provide for delay of the base signal and may not require feedback protection for the final amplifier stage. Each channel includes a bandpass filter 64, an equalizer 66, dynamic phase adjustment 68 and final stage amplification 70. Channels B, C and D add delay elements 72 and amplification stage feedback protection 74.

FIG. 9 illustrates stacking a pair of acoustic radiators 10 into a omni-directional line array 500. More than two acoustic radiators 10 can be stacked into the array. The stacks can be built from acoustic radiators including or not including radial baffles 32.

What is claimed is:

1. An acoustic radiator for suppression of cavitation in a liquid transmission medium, the acoustic radiator comprising:

- an interior face;
- an interior boundary located opposed to and spaced from the interior face;
- a central core connecting the interior face to the interior boundary; and
- a plurality of submersible transducers distributed on the interior face and oriented to radiate sound away from the interior face against the interior boundary where the sound is contained and directed across the interior boundary and the interior face, the plurality of submersible transducers being organized into at least first and second sub-arrays, the second sub-array being located in succession to the first sub-array as determined by a primary local direction of propagation of the reflected sound.

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2. The acoustic radiator of claim 1, further comprising a half shell and a disk baffle to support the interior boundary and the interior face, respectively, the half shell and the disk baffle defining a toroidal waveguide having a central core providing for globally omni-directional radiation of sound from the central core to a mouth and outwardly from the mouth.

3. The acoustic radiator of claim 2, wherein the interior face is one of first and second major surfaces of a disk baffle, with first and second interior boundaries opposing the first major surface and a second major surface of the disk baffle, respectively, and pluralities of submersible transducers being distributed on the first and the second major surfaces of the interior baffle in two toroidal waveguides.

4. The acoustic radiator of claim 2, including a plurality of toroidal waveguides stacked into a waveguide.

5. The acoustic radiator of claim 3, further comprising: the submersible transducers being piezoelectric devices.

6. The acoustic radiator of claim 5, further comprising: the successive sub-arrays of submersible transducers including greater numbers of transducers with increasing proximity to the mouth.

7. The acoustic radiator of claim 6, further comprising: at least a first radial baffle extending to the mouth of the toroidal waveguides.

8. The acoustic radiator of claim 6, further comprising: a plurality of radial baffles extending from the central core to the mouth dividing each toroidal waveguide into a plurality of signal channels within each toroidal waveguide.

9. An acoustic radiator comprising:

- an arcuate mouth;
- a waveguide extending from the mouth to a base, the waveguide being defined by first surface and a second opposed surface;
- a plurality of water submersible acoustic transducers distributed along one of the first and the second opposed surface; and
- drive circuitry for the water submersible acoustic transducers for synchronously reinforcing a sound wave propagating along the length of the waveguide from the base to the arcuate mouth by operating those of the plurality of water submersible acoustic transducers on the first surface.

10. The acoustic radiator of claim 9, wherein the plurality of water submersible acoustic transducers reinforce the sound wave keeping a stable frequency spectrum.

11. The acoustic radiator of claim 10, further comprising: the plurality of water submersible acoustic transducers being organized into sub-arrays defined by distance of the acoustic transducers in a sub-array from the arcuate mouth; and

a ratio of the surface area of the water submersible acoustic transducers in any sub-array relative to the length of the arc of the sub-channel for the sub-array being a constant.

12. The acoustic radiator of claim 11, further comprising: a second waveguide with water submersible acoustic transducers mounted in a baffle providing major surfaces for the first surface for both the first and second sound channels.

13. The acoustic radiator of claim 12, further comprising: ring dampening elements positioned between the first and second surfaces of the sound channels.

14. An acoustic radiator comprising: an arcuate waveguide, which may be extended through a full circle to form a toroidal waveguide; the arcuate waveguide including first and second facing interior surfaces forming wave propagation boundaries;



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a plurality of liquid submersible acoustic transducers arranged in a constellation along one of the first and second facing interior surfaces;  
the plurality of liquid submersible acoustic transducers being oriented to direct sound at the remaining facing interior surface; and  
the waveguide terminating at a mouth.

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**15.** The acoustic radiator of claim **14**, further comprising: radial baffles dividing the arcuate waveguide into radial channels.

**16.** The acoustic radiator of claim **15**, including a plurality of toroidal waveguides stacked into a waveguide.

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